MINIMAX DISAPPOINTMENT CRITERION FOR VIDEO BROADCASTING

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ABSTRACT

Users of media broadcasting services generally experience different grades of overall performance because of the non-uniform quality of their channel conditions. In order to provide all users equally satisfactory performance, we propose a new performance criterion named "minimax disappointment", based on layered service levels and the basic principle of joint source-channel coding [1]. This criterion minimizes for all users the maximum value of performance degradation between the received performance and the expected optimal performance, given each user's individual channel situation. In support of this criterion, we develop two broadcasting systems and a gradient-based optimization scheme. Our systems achieve universally near-maximal performance for multiple user classes by providing layered service. [1]

1. INTRODUCTION

In a broadcasting situation, the central broadcasting station transmits the same set of signals to all users of its service without regard to their individual connection to the station. Received performance for different users may vary because of different channel qualities. A typical example would be a simple wireless broadcasting scenario, where users are scattered in a pattern of co-centered circles of different radii (shown in Figure 1); depending on their respective distances to the station and other factors such as geographical environment, structure density, local weather and electromagnetic noise activity, etc; users can be categorized into different classes that observe different channel signal-to-noise ratios (SNR). In general, the farther away the user is from the station, the worse the transmission quality because of signal energy decay over distance.

In view of the above situation, it is considered good practice to define multiple user classes and provide layered levels of service. In other words, the broadcast signal is divided into multiple successively refinable layers; each class of users can then receive a maximum number of layers within its ability and obtain a satisfactory performance.

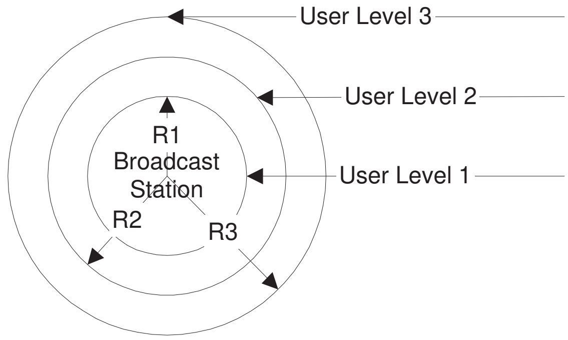

Fig. 1. Broadcasting and User Levels

However, different classes of users still receive unequal performance in spite of the performance increase provided by layered service. How to effectively and meaningfully evaluate the performance of the overall broadcasting system, given different classes of users, has been a major concern in the development of broadcasting schemes. Traditionally people have developed heuristic and intuitive measures such as averaging the individual performance over all users, using weighted averaging schemes, or simply designing for the worst-case user. They either penalize certain class(es) of users, or are too ad-hoc to retain much theoretical significance.

We believe that a desirable and practical broadcast performance criterion should possess the following properties:

- Fairness: no class of users should be penalized or weighted more than the other classes.
- Individuality: we should take into consideration the fact that different class of users do have different service quality *expectations* because of their respective channel situations (assuming that they are reasonably *informed*).
- Tractability: we should be able to obtain the solution to the optimization problem based on the perfor-

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mance measure using established optimization methods, and the performance measure itself should have underlying theoretical significance.

Based on the observations above, in analogy to the *minimax regret* criterion in decision theory, we propose a new broadcast performance measure named "minimax disappointment", which can be expressed by the following formula:

$$P = \min\left(\max_i (P_i - p_i)\right) \quad i = 1, \ldots, N$$

where N is the number of user classes, P_i is the ith user's *expected best performance* (our contribution lies in pointing out that this P_i can be obtained using the joint source-channel coding principle), and p_i is its actual *received performance*. Intuitively, for most users $P_i > p_i$ because we have to trade off between multiple users.

Our objective is to minimize the maximum performance degradation for all users; in other words; all users will be "disappointed" to a certain extent because they cannot receive their expected optimal performance, and the maximum value of their "disappointment", P, is the proposed performance measure: the smaller P is, the better the performance.

This performance measure does not penalize any class of users, and it is reasonable and fair because all users know that everybody else is equally as satisfied/disappointed as they are. It is theoretically tractable because optimizing the performance simply falls into the Minimax Optimization framework.

In the following sections we give a brief introduction to joint source-channel coding principle, discuss two example systems and the optimization algorithm we use, and present the simulation results.

2. BACKGROUND KNOWLEDGE

2.1. Joint Source-Channel Coding

Joint source-channel coding (JSCC) [1] is an increasingly popular concept in designing efficient and error-resilient communication systems. The basic idea behind JSCC is to intelligently allocate limited system resources (such as bandwidth, power, etc.) between source and channel coders so that we precisely provide the necessary amount of protection, without wasting extra resources on channel coding. In a point-to-point transmission channel with reliable feedback, JSCC can be utilized to yield significant performance increase [2]. In a broadcasting channel where there is no feedback, we could still optimize a transmission system with regard to a certain class of users and obtain its expected best performance, P_i.

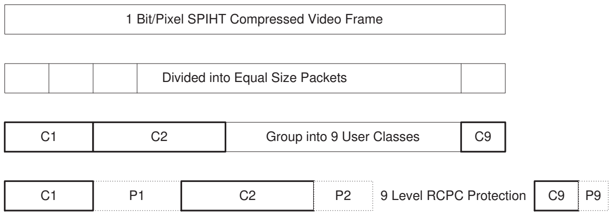

Fig. 2. Rate-Constrained System

2.2. Source-Channel Coders

For video source compression, the Motion-SPIHT [3] and 3D-SPIHT [4] coders are used because of their excellent progressive property, which is essential for layered service. For channel coders we have chosen the Rate-Compatible Punctured Coder (RCPC) [5]. We also experimented with systems where we adjust the transmission power for each bit instead of a single overall channel protection rate.

3. BROADCASTING SYSTEMS

Our minimax disappointment approach is very general and can be applied to a variety of possible systems. In this section we discuss in detail the two example broadcast systems we designed and the optimization algorithm we use.

3.1. Broadcasting System with Rate Constraint

In the rate-constrained broadcasting system, we implement layered service by assigning different channel protection rates to layers of different importance.

The encoding procedure is illustrated in Figure 2.

1 Raw video frames (indexed by i) are compressed equally at one-bit-per-pixel using the Motion-SPIHT encoder, and their respective rate-distortion functions are estimated.

2 Each frame is divided into fixed-size packets, of which only the first K_i (i is the frame index) will be sent. These K_i packets are grouped into J packet groups, where J is the number of available RCPC protection rates. The jth packet group for frame i contains m_{ij} packets, where the m_{ij} are not necessarily equal. The values for K_i, m_{ij} are determined by the system to yield the optimal performance, which, in our case, is the minimax disappointment for all the users.

3 RCPC protection of rate r_j is applied to the packet group j, which is then broadcast.

The minimax optimization problem can be shown mathematically as follows:

$$
\begin{aligned}
K_i &= \sum_{j}^{J} m_{ij} && (1)\\
s_i &= \sum_{j}^{J} m_{ij}\, r_j\, p && (2)\\
D_{i,l} &= \sum_{k=1}^{K_i} \left[P_{k+1,l} \sum_{n=1}^{k} (1 - P_{n,l}) \right] d_i(k) && (3)\\
P &= \max_{l} \left(D_{0,l} - \frac{\sum_i^N D_{i,l}}{N} \right) && (4)\\
b_i &= \max(b_{i-1} + s_i - R, 0) && (5)\\
b_i &\leq b_{max},\ i = 1, 2, \ldots, N && (6)
\end{aligned}
$$

where K_i, m_{ij}, r_j are defined as before, p is the fixed packet size in bytes, s_i is the total transimssion length (source plus protection) for the ith frame, $D_{i,l}$ is the expected received distortion for the ith frame by the lth user, and $d_i(k)$ is the distortion of the decoded ith frame if the kth packet is the first packet lost. $P_{n,l}$ is the transmission failure probability of the nth packet for the lth user (the m_{ij} packets in the jth packet group would have $P_{n,l}$ equal to the error probability for user l when using RCPC protection rate r_j). Minimizing $D_{i,l}$ in (3) solves the JSCC optimization for each user class and yields $D_{0,l}$, the expected optimal performance for user l. Minimzing P in (4) solves the minimax optimization for the entire system and yield the minimax disappointment. Equations (5) and (6) are rate-control-related constraints which further complicate the optimization problem.

To solve this optimization problem, we initialize the values for m_{ij} with the expectation that they are close to the optimal values, and employ a gradient-based procedure to derive the optimal solution (please note that in our simulation we minimize P using the log-scale PSNR instead of distortion). Usually more than five iterations are required for the algorithm to converge, but since broadcasting parameter optimization is usually done offline, we can afford the delay.

3.2. Power-Constrained Broadcasting System

In the power-constrained broadcast system, we implement layered service by adjusting the transmission power for each bit in the video source bit-stream.

The encoding procedure (shown in Figure 3) can be described as follows:

1 Raw video frames are first divided into groups of size 16 and compressed using the 3D-SPIHT video encoder; its rate-distortion curve is then estimated.

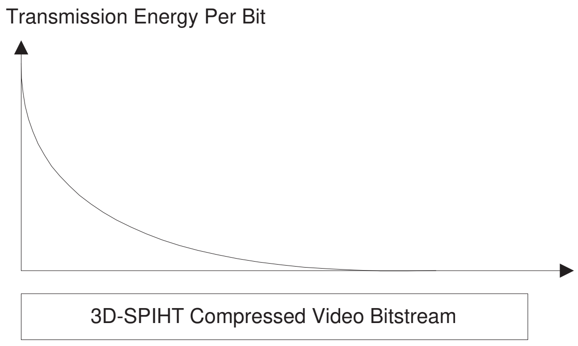

Fig. 3. Power-Constrained System

2 The compressed video source stream is transmitted with power per bit optimized under the total power constraint.

The minimax optimization problem can be cast mathematically as follows:

$$
\begin{aligned}
p_k(e_j) &= Q\left(\sqrt{\frac{2e_j}{N_{0,k}}}\right) && (7)\\
D_k &= \prod_{j=1}^{L_s} (1 - p_k(e_j))\, D_c + \\
&\quad \sum_{i=1}^{L_s} \left[\prod_{j=1}^{i-1} (1 - p(e_j)) \right] p_k(e_j)\, d(i) && (8)\\
P &= \max_{k} (D_{0,k} - D_k) && (9)
\end{aligned}
$$

where $p_k(e_j)$ is the transmission error probability for the jth bit for the kth user, given bit power e_j and channel noise $N_{0,k}$; D_k is the resulting distortion for the kth user; L_s is the total number of bits; D_c is the distortion caused by source compression; $d(i)$ is essentially the rate-distortion curve for the current video stream; it is the decoding distortion if the ith bit is the first bit in error (we discard all bits after it); $D_{0,k}$ is the expected optimal performance for the kth user and P is the maximum disappointment value for all users.

We try to minimize P by finding the optimal power allocation vector E $(e_1, e_2, \ldots, e_{L_s})$. This minimax optimization problem can be similarly solved by a gradient-descent algorithm.

Since we are optimizing with regard to each bit, the scale of the optimization problem can become relatively large when we have a large number of bits to transmit. In simulation we observed that when we have a reasonable number of user classes (more than seven), whose channel SNRs are spread out, the optimal power allocation vector for the minimax optimization problem is approximately a linear combination of all the optimal power allocation vectors for the

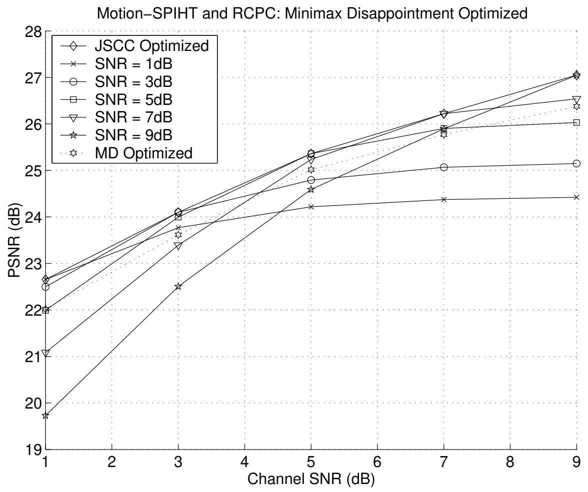

Fig. 4. Rate-Constrained System Simulation Result

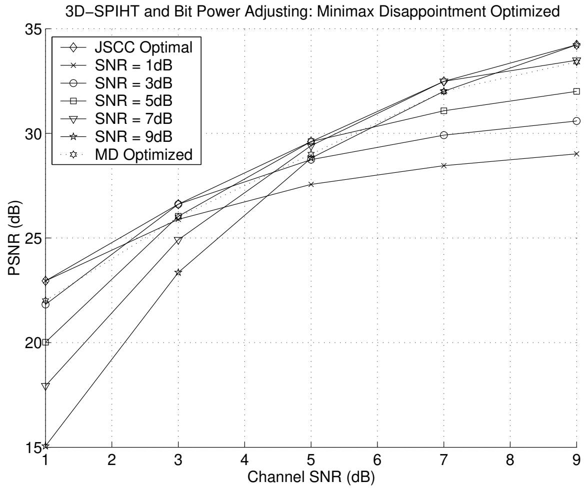

Fig. 5. Power-Constrained System Simulation Result

joint source-channel coding problem for each individual user class. Thus, we can reduce the dimension of the problem down to less than 10 variables and apply the same gradient algorithm.

4. SIMULATION RESULTS

From Figure 4 and 5 we observe that the received performance for all users of our system is roughly the same distance from their individual expected best performance; in other words, they experience the same level of disappointment, whereas in the other fixed-protection system configurations, one or more users are always highly disappointed; i.e, their received performance is far below their best expectation. Thus, our system does give the optimal performance in terms of the minimax disappointment criterion, achieving maximum disappointments of 0.67 dB and 0.98 dB, respectively.

5. CONCLUSIONS

Video broadcasting systems have always been in need of an intelligent and meaningful performance criterion that supports a desirable trade-off between multiple classes of users and remains tractable. In this paper we introduce the maximum value of the deviation between received performance and expected best performance for each user as a new performance criterion. It is a fair criterion toward all users, and theoretically appealing because it falls into the minimax optimization framework. We observe that little penalty is paid for layered service levels; our simulation showed less than 1 dB of performance loss for five user classes.

The minimax disappointment optimization achieves almost equal disappointment for multiple classes of users, each corresponding to a particular received SNR. However, equal disappointment is not guaranteed for SNRs between these levels. A smoother distribution of disappointment *vs.* SNR can be achieved by increasing the number of user classes, and arbitrary precision can be obtained by introducing a sufficiently large number of user classes. A gradient-based algorithm effectively finds the optimal operating parameters.

6. REFERENCES

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